

# An overview of the completed Canada-France-Hawaii Telescope Lensing Survey (CFHTLenS)

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The Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) represents the most powerful weak lensing survey carried out to date. The CFHTLenS (Canada-France-Hawaii Telescope Lensing Survey) team was formed in 2008 to analyse the data from the CFHTLS focussing on a rigorous treatment of systematic effects in shape measurements and photometric redshifts. Here we review the technical challenges that we faced in analysing these data and their solutions which set the current standard for weak lensing analyses. We also present some science highlights that were made possible by this effort including cosmic shear tomography, tests for modified gravity models, and the mapping of dark matter structures over unprecedentedly large scales. An outlook is given on current and future surveys that are analysed with the tools prepared for CFHTLenS. **CFHTLenS represents the first and only weak lensing data set that has been made publicly available so far.** We encourage other surveys to follow this example.

## 1 Introduction

The first observations of cosmic shear (Bacon et al. 2000; Van Waerbeke et al. 2000; Wittman et al. 2000) opened up a new window to study cosmology. Measuring the build up of the large scale distribution of dark matter structures over cosmic time with cosmic shear tomography represents a very powerful cosmological tool that ideally complements the high-redshift observations of the cosmic microwave background (CMB) with observations at low-redshift. Large volumes have to be surveyed to yield cosmologically meaningful results, and the three-dimensional distribution of structures has to be resolved for the tightest cosmological constraints. These requirements naturally lead to the design of deep multi-band imaging surveys over large areas of the sky with the data being taken under the best possible seeing conditions. The multi-band data are important for estimating photometric redshifts of millions of background galaxies that are used for the lensing measurement whereas the high-resolution is crucial for measuring accurate ellipticities for the same objects.

The Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) is the most ambitious project with such a focus that has been completed so far. Here we describe the work of the CFHTLenS (Canada-France-Hawaii Telescope Lensing Survey) team that was formed to analyse the data from the CFHTLS focussing on a rigorous treatment of the main sources of systematic errors in such an analysis. In Sect. 2 we describe the CFHTLS data set and in Sect. 3 we illustrate some of the technical challenges that we were faced with analysing those data. Section 4 presents a few highlights from the scientific papers that were made possible by the unprecedented quality of the CFHTLenS data products. In Sect. 5 we give an outlook and report on some projects that are currently carried out with the tools developed for CFHTLenS.

## 2 The CFHTLS

CFHTLenS is based on the Wide part of the CFHTLS, an imaging survey carried out with the MegaCam instrument mounted at the CFHT. It consists of 171 pointings of this 1 square degree camera, which are arranged in four different contiguous patches to allow observations all year. All patches are located at high-galactic latitude and three of them are close to the equator whereas one is at higher declination. All pointings have been observed in the *ugriz*-bands to a  $5\sigma$  depth of 25.2, 25.6, 24.9, 24.6, and 23.5, respectively. The best seeing time is reserved for the *i*-band data so that the data from this band with a median seeing of  $0''.7$  are ideally suited for weak lensing shape measurements.

## 3 Data analysis

### 3.1 The CFHTLenS team

The CFHTLenS team was formed to re-analyse the CFHTLS data with the goal of understanding all systematic effects that affect cosmic shear science to a level that is better than the statistical precision of this data set. To reach this goal we apply and further develop the most advanced shape measurement and photometric redshift (photo- $z$ ) algorithms. The team originally consisted of members from different European countries and Canada which had been working together on the STEP shape measurement challenge (Heymans et al. 2006) and other projects.

### 3.2 Data reduction

All MegaCam data are pre-reduced at the Canadian Astronomical Data Centre (CADC). We are using these pre-reduced individual exposures as the basis for our data reduction. Subsequent reduction steps are carried out with the THELI wide-field imaging reduction pipeline (Schirmer et al. 2003; Erben et al. 2005). These include astrometric and photometric calibration, stacking, masking, and creation of weight and flag images. Details can be found in Erben et al. (2013). While the deep stacks are used for the extraction of multi-colour photometry we measure galaxy shapes from individual exposures to avoid a number of systematic effects that are created by the stacking procedure.

### 3.3 Photometry and photo- $z$

The point spread function (PSF) is typically different in the different bands of a pointing. In order to extract accurate colours for all objects this has to be accounted for. We convolve the five images (i.e. the *ugriz* stacks) of one pointing so that the PSF in all bands is Gaussian and has the same size. This is done with the shapelet-based code described in Kuijken (2008).

The photometry is then extracted from these Gaussianised stacks with SExtractor (Bertin & Arnouts 1996) in dual-image mode. The unconvolved *i*-band image is used for detection. This procedure yields unbiased colours with close to optimal signal to noise ratio (S/N).

Photometric redshifts are then estimated with the BPZ photo- $z$  code (Benítez 2000) and the results are compared to different spectroscopic redshift catalogues that are overlapping with the CFHTLS footprint. Details of the multi-colour photometry and photo- $z$  methods can be found in Hildebrandt et al. (2012).

### 3.4 Shape measurement

A particular focus within CFHTLenS is given to shape measurements (Miller et al. 2013) since this area had been identified as being affected by different systematic effects. In particular

redshift dependent systematics<sup>a</sup> are harmful for cosmic shear tomography, one of the main science drivers for CFHTLenS. While we started with a number of different shape measurement techniques we quickly concentrated on the Bayesian *lensfit* algorithm (Miller et al. 2007; Kitching et al. 2008) that showed the most promise to meet our requirements.

*LensFit* is a Bayesian forward fitting shape measurement code that employs a suite of analytical galaxy light profiles convolved with the measured PSF to fit the data. The resulting multi-dimensional likelihoods are then multiplied with empirical prior distributions for galaxy size, ellipticity, and bulge to disk ratio to yield a posterior probability distribution. Marginalising over all uninteresting parameters then yields an unbiased estimate of the ellipticity of each galaxy. Furthermore, a weight is calculated that parametrises the error of the ellipticity measurement and can readily be used in shear measurements to properly weigh background sources.

As mentioned above *lensfit* is run on the individual, astrometrically-calibrated exposures. Results from different exposures of one field (typically 7 per field) are combined in a statistically optimal way. Working on individual exposures instead of stacks has the advantage that different PSFs are not mixed. Besides that, it also avoids the correlation of noise that is an inevitable result of sub-pixel stacking.

### 3.5 Tests for shape systematic

An important aspect of the work of the CFHTLenS team is the development of cosmology-independent systematic tests to check the robustness of the shear catalogue.

The most important tool to identify residual effects from an imperfect PSF correction is the star-galaxy cross-correlation function (Heymans et al. 2012). Here, the shapes of the corrected galaxies are cross-correlated with the shapes of the uncorrected stars that were used to measure the PSF. Naively one could assume that a signal significantly different from zero would indicate the presence of residual systematics. However, not only shot noise contributes here, and the significance has to be estimated taking into account a signal that can be created by cosmic shear itself (see Heymans et al. 2012, for details). This means that the amplitude of the star-galaxy cross-correlation function has to be compared to results from detailed simulations with - by construction - perfect PSF correction. We find that the amplitude of the star-galaxy cross-correlation function for all fields is considerably higher than the one found in the simulations. However, this undesired signal is dominated by a few fields that seem to have larger systematic errors than others. Rejecting  $\sim 25\%$  of the fields with the strongest star-galaxy cross-correlation leads to a star-galaxy cross-correlation function amplitude consistent with simulations.

We also run *lensfit* on detailed image simulations that are carefully matched to the data in terms of the distributions in ellipticity, S/N, size, and bulge to disk ratio (Miller et al. 2013). This is done to test the output ellipticities  $e_1$  and  $e_2$  against the known input ellipticities as functions of S/N and size (both of which can be relatively easily be measured from the data itself). This reveals some residual multiplicative biases that we correct for on a object-by-object basis in the data. Note that this kind of bias is expected in noisy measurements and can not be completely avoided.

The image simulations do not reveal any additive bias. However, averaging the  $e_2$  ellipticity component for all CFHTLenS data reveals some residual bias that is significantly different from zero. We characterise this bias as a function of size and S/N and subtract it from the measured  $e_2$  (Heymans et al. 2012).

The combination of rejecting fields with bad PSF (identified by their anomalously high star-galaxy cross-correlation) and the correction of all residual biases with image simulations and directly from the data yields a state of the art shear catalogue that is free from systematic errors to the level required by the size of the CFHTLS.

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<sup>a</sup>Those can originate from flux/size dependent systematics and the correlation between redshift and flux/size.

## 4 Science highlights

### 4.1 Cosmic shear

One of the main science drivers of CFHTLenS is cosmic shear tomography. Measuring the statistical properties of the large scale structure of the dark matter density field over cosmic time has become one of the most promising cosmological tools. This cosmological probe is studied in great detail in a number of CFHTLenS publications (Kilbinger et al. 2013; Benjamin et al. 2013; Heymans et al. 2013; Kitching et al. 2014; Fu et al. 2014).

A pure 2D cosmic shear analysis is presented in Kilbinger et al. (2013) where the individual redshifts of the sources are not taken into account and the colour information are purely used to constrain the redshift distribution. In this paper we explore different ways of measuring the signal from small, non-linear scales out to large radii ( $\gtrsim 2^\circ$ ). It is shown how such measurements yield tight constraints on the total cosmic matter density,  $\Omega_m$ , the amplitude of the fluctuations of the matter power spectrum,  $\sigma_8$ , and the curvature,  $\Omega_K$ . These constraints are complementary to constraints from the CMB and improve on what has been found in the seven-year data set of the WMAP satellite (Komatsu et al. 2011). An extension of this 2D cosmic shear measurement to third-order statistics can be found in Fu et al. (2014). It is shown that these higher-order statistics add some statistical power to the cosmic shear result at the expense of more complicated systematic errors.

For tomographic cosmic shear we split up the source sample into different redshift bins. A basic tomography study with two broad redshift bins and concentrating on the systematic robustness of the photo- $z$  is presented in Benjamin et al. (2013). A much more detailed cosmic shear tomography measurement is presented in Heymans et al. (2013). There we split up the source sample into six narrower redshift bins and measure all 21 possible shear cross- and auto-correlation functions. In this study we also correct for the major astrophysical systematic associated with cosmic shear measurements: intrinsic alignments of galaxy ellipticities, which are especially important at low redshift. The inclusion of redshift information yields tighter constraints on the cosmological parameters discussed above and allows for testing the dark energy equation of state,  $w$ . Assuming flatness and combining our results with different external data sets we constrain this crucially important cosmological parameter to  $w = -1.02 \pm 0.09$ .

Instead of binning galaxies in discrete photo- $z$  bins one can also use the redshift information for each galaxy individually. This is known as 3D cosmic shear and an application to CFHTLenS is presented in Kitching et al. (2014). Taking into account the full redshift probability distribution of each object that is provided by the photo- $z$  code we can suppress non-linear scales much more rigorously. This is advantageous because it means that we can compare our measurements to theory in a regime where cosmic structure formation is better understood than on the small scales where baryonic effects and non-linear evolution play a great role. Hence, the uncertainty of the models is considerably reduced. It is clear that precision suffers if the small scales with high S/N are neglected. However, this is not a problem of 3D cosmic shear itself (it could easily be used on smaller scales) but rather stresses the importance of better modelling these small-scale effects for future dark energy mission which will have considerably greater statistical power.

### 4.2 Modified gravity

One of the most interesting aspects of cosmic shear tomography is that it is sensitive to both measurable effects of dark energy, the influence dark energy has on the geometry of the Universe as well as on the growth of the large scale structure. It is the combination of these two different aspects that has the potential to reveal deviations from general relativity and test alternative theories of gravity. This becomes even more powerful when cosmic shear is combined with a tracer of non-relativistic physics. In Simpson et al. (2013) we use redshift-space distortions

(RSD) from the WiggleZ dark energy survey (Drinkwater et al. 2010) and 6dFGS (Jones et al. 2009) for that purpose. Combining these RSD measurements with the 2-bin cosmic shear tomography results from Benjamin et al. (2013) we obtain constraints on several parametrisations of modified gravity models. All our constraints are compatible with general relativity excluding large parts of the parameter space for possible deviations. This study illustrates the power of this combination to potentially falsify one of the pillars of our physical world model, and such measurements are the basis for very large projects that are starting just now (e.g. 2dFLens).

### 4.3 Dark matter maps

The large contiguous patches of CFHTLenS and the high-quality data resulting in high number densities of lensing sources represent ideal conditions for mapping the dark matter distribution directly. This creation of mass maps and their scientific exploitation is described in Van Waerbeke et al. (2013). The value of these maps goes beyond the mere visualisation of dark matter structures. Maps are especially useful to study higher-order statistics and the relationship between luminous and dark matter (see also Van Waerbeke et al. 2013). The CFHTLenS dark matter maps are the largest created so far and reveal giant voids on scales of several degrees that were undetectable with previous surveys. Furthermore, the maps offer the exciting opportunity to cross-correlate the dark matter structures to signals extracted from very different experiments (for an example see Van Waerbeke et al. 2014).

## 5 Summary and outlook

The work of the CFHTLenS team represents the next crucial step in controlling systematic effects in state of the art weak gravitational lensing surveys. The analysis tools developed in the course of the project go a long way beyond what has been used in the past and form the basis for current and upcoming Stage III and IV weak lensing projects that are 1-2 orders of magnitude larger than CFHTLS and require much tighter control of systematic errors.

In certain areas (dark energy equation of state, modified gravity parameters, dark matter mapping) the data analyses from CFHTLenS yield competitive or even unprecedented results showing the full potential of weak lensing as a cosmological tool. The scientific relevance of CFHTLenS goes beyond pure cosmological results, and the data have been used by the CFHTLenS team for studies of galaxy evolution (Simon et al. 2013; Hudson et al. 2013; Velander et al. 2014) as well as galaxy group and cluster science (Milkeraitis et al. 2010; Gillis et al. 2013; Ford et al. 2014).

The CFHTLenS data are publicly available at <http://www.cfhtlens.org> as well as at <http://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/community/CFHTLenS/query.html>

We provide calibrated images, photometry and shear catalogues, masks, random catalogues matching the geometry of the data, cosmological data vectors for several of the measurements discussed here, covariance matrices, and redshift distributions. The data have been downloaded by a large number of different researchers (as evidenced by the number of unique IP addresses), and a growing number of external papers using CFHTLenS data are coming out. **It should be noted that CFHTLenS is the only weak lensing data set that has been released publicly so far.** We strongly encourage the community to follow our example and support the credibility of weak lensing as a cosmological tool in general and our understanding and treatment of systematic effects in particular through open access of weak lensing data.

The suite of tools developed within CFHTLenS is currently being applied to a number of similar surveys. CFHTLenS members are strongly involved in the European Kilo Degree Survey (KiDS de Jong et al. 2013) as well as in a re-analysis of the data from the Red Sequence Cluster Survey 2 data (this project is dubbed RCSLenS<sup>b</sup>). Combined with similar data analysis on

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<sup>b</sup><http://www.rcslens.org>

smaller projects like CS82 (CFHT Stripe 82 Survey), NGVS (Ferrarese et al. 2012, The Next Generation Virgo Survey), and CODEX (weak lensing calibration to Constrain Dark Energy with X-ray clusters) this will yield a state of the art lensing data set of  $\sim 3000\text{deg}^2$  in the near future rivalling a project like the Dark Energy Survey in area and surpassing it in image quality. We feel committed to make also these data publicly available once the main science analyses by the teams are done.

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